Appendix B

Roadmap: Answers to PAC Questions

After reviewing the BTeV PTDR submitted in May of 1999, the PAC made several useful observations and noted several issues that warranted special priority for further study. In this appendix we summarize the results of the studies recommended by the PAC, and point to the portions of the proposal where each issue is addressed in detail.

Before addressing each of the issues raised, we would like to emphasize a few of the more interesting developments that have occurred since the PTDR:

- The number of planes in each station of the baseline pixel detector is now two instead of three. This significantly reduces the amount of material and complexity of the system without diminishing the tracking and triggering performance.

- The performance of the BTeV Level 1 pixel trigger is similar to that described in the PTDR even with 2/3 as many pixel planes. Unlike in the PTDR, we have used a full GEANT event simulation and introduced non-Gaussian tails to the hit distributions based on data from our 1999 beam tests. The simulation included underlying events, multiple interactions, and full pattern recognition. Selecting Level 1 trigger "cuts" to give us a rejection for minimum bias events of 100, we find that the trigger efficiency for several modes of interest are generally much better than 50%. We have found that this performance is robust with respect to pixel inefficiencies and noise, multiple interactions, and beam misalignments.

- BTeV's ability to study states with γ's and π^0's using its $PbWO_4$ electromagnetic calorimeter has been validated. Using full GEANT simulations with a complicated underlying event and accompanying minimum bias events, we can successfully reconstruct even the very low energy photons from these decays and can suppress the combinatoric background. We expect to reconstruct a factor of 7 more $B \to \rho\pi$ decays than LHC-b with a factor of 5 better signal-to-background.

- We were asked to include beam related backgrounds in our studies. At present, the C0 interaction region is still being designed. However, the Beams Division assured us that they now know how to reduce these backgrounds to levels much smaller than the physics related backgrounds. We do show that our Level 1 pixel trigger is extremely robust, even at noise levels much larger than expected. Another detector system that could conceivably suffer is the muon system, and there the problems would be close to the beam. Our muon trigger does not rely on the tubes near the beam pipe.

The items requested by the PAC can be broken down into four categories: (1) physics studies, (2) trigger/detector studies, (3) comparisons to other experiments, and (4) staging and commissioning scenarios.

B.1 Physics Studies

The PAC requested a thorough study of six processes that "have a particularly important role to play both in the extraction of fundamental physics and in the decision of whether the proposal will be approved." For three processes a full GEANT simulation was recommended ($B \to \rho\pi$, $B_s \to D_s K$, and $B \to D^*\rho$) and for the other three ($B \to J/\psi K_s$, $B^- \to D^0 K^-$, and $B_s \to D_s\pi$) a thorough study using MCFast was thought to suffice.

The following elements were to be included in each study:

- Assumptions of a luminosity of 2×10^{32} cm^{-2}s^{-1} and a running time of 10^7 sec/year.
- Detailed and realistic simulations, including both physics and beam related backgrounds, secondary interactions and decays, all significant environmental effects such as multiple interactions, and detector/electronics noise.

Part III of this proposal discusses the studies we have made of the six requested modes. Each includes the above elements. In particular, we have used BTeVGeant (described in Section 12.1) for modes where a full GEANT simulation was requested. A summary of each is given below, along with pointers to where in the proposal one can find detailed descriptions.

B.1.1 $B \to \rho\pi$ (BTeVGeant study)

The PAC noted that this was a mode for which we would be expected to do substantially better than LHC-b. They pointed out that in our studies for the PTDR we did not include backgrounds, and requested "a convincing statement of the uncertainty in $\sin(2\alpha)$ which could be expected from BTeV."

This study is described in detail in Section 16.5, and is summarized again in Part IV. We expect to reconstruct a factor of 7 more $B \to \rho\pi$ decays than LHC-b with 5 times better signal-to-background (see Part IV).

The reconstruction efficiencies for $B \to \rho\pi$ and backgrounds were studied using a full GEANT simulation (BTeVGeant). All signal and background samples were generated with a mean of two interactions per crossing. For the backgrounds, this required generating 4.5×10^6 $b\bar{b}$ events. Almost 90% of the time spent in generating these events is in the electromagnetic calorimeter simulation.

We expect to have $\sim$1000 effective flavor tagged $\rho^{\pm}\pi^{\mp}$ events and $\sim$150 $\rho^0\pi^0$ per year with signal-to-background ratios of approximately 4:1 and 1:3, respectively. We expect to continue our Monte Carlo production in order to build up a large enough sample of background events to study how to improve this. We have not done a full simulation of our sensitivity to α. Final results will depend on several unknown quantities including the branching ratio for $\rho^0\pi^0$ and the ratio of tree to penguin amplitudes. Analysis by Snyder and Quinn [1] showed that with 2,000 background free events they always found a solution for α and the accuracy was in the range of 5-6^o. We can collect these events in 2×10^7 seconds, but we will have some background. Furthermore, Quinn and Silva have proposed using non-flavor tagged rates as input that should improve the accuracy of the α determination [2].

B.1.2 $B_s \to D_s K$ (BTeVGeant study)

The PAC pointed out that since this final state must be distinguished from $D_s\pi$, excellent particle identification is crucial. They requested that we study this mode using a more detailed simulation of our K/π separation so that a more realistic assessment can be made.

We have presented this study in Section 16.4.1. We used a detailed simulation of the RICH detector described in Chapter 6 to study the efficiency of the signal vs. efficiency of the background from misidentified pions. We expect that $B_s \to D_s\pi$ will be the largest source of background (although we investigated others) and estimate a signal-to-background level of $\sim$7. Using the estimates of branching fractions given by Aleksan *et al.* [3], we expect to have about 13,100 reconstructed events per year. This will result in a measurement error on γ of about 7^o.

We note that we expect to reconstruct 70% more of these decays than LHC-b at the same signal-to-background (see Part IV).

B.1.3 $B \to D^*\rho$ (BTeVGeant study)

We were asked to fully investigate the decay $B \to D^*\rho$ as a benchmark of our ability to reconstruct modes with π^0's. The results of this study, which used BTeVGeant, are presented in Section 16.3 and compared to the CLEO result for this decay.

We find that the signal to background expected in BTeV compares very favorably with that obtained by CLEO, and is expected to improve simply by optimizing the cuts after the backgrounds are studied in detail. The event yield per year is more than 230 times higher than that expected from each of the e^+e^- B-factories.

This analysis demonstrates BTeV's ability to study states with γ's and π^0's. We have shown that even with a complicated underlying event and accompanying minimum bias events, we can successfully reconstruct the very low energy photons from these decays and can suppress the combinatoric background.

B.1.4 $B \to J/\psi K_s$ (MCFast study)

The PTDR quoted a sensitivity to $\sin(2\beta)$ based on a time integrated measurement and stated that a time dependent measurement would be more sensitive. The PAC asked that the time dependent sensitivity be determined, and asked that we make a more detailed study of tagging efficiencies.

The tagging study is presented in Chapter 15. The sum of all our tagging efficiencies is 15% but there are correlations. Our initial attempt to account for these correlations gives us a tagging efficiency of 9% but there are known deficiencies in the way we have handled events with more than one tag. As a result, we have continued to use the 10% we used in the PTDR but expect to do better when we complete our study.

The time dependent determination of $\sin(2\beta)$ from $B \to J/\psi K_s$ is presented in Section 16.2. We find that in one year of running our uncertainty on $\sin(2\beta)$ is 0.025. As expected from analytic calculations, this is 20% better than the time integrated method.

B.1.5 $B^- \to \overline{D^0}K^-$ (MCFast study)

In the PTDR a study of this mode was presented without a discussion of backgrounds. The committee requested a complete analysis in order to judge BTeV's sensitivity in this mode.

It was found (see Section 16.4.2) that only background arising from real D^0's need be considered, and that $b\bar{b}$ events were the major contributor (as opposed to $c\bar{c}$). The expected signal-to-background ratio for the $(K\pi)K^-$ mode is 1:1. The signal-to-background for the $(KK)K^-$ mode is better.

We expect to reconstruct about 300 $B^\pm \to (K\pi)K^\pm$ and 2,000 $B^\pm \to (KK)K^\pm$ per year at the design luminosity of 2×10^{32} cm^{-2}s^{-1}. With this number of events, γ can be measured to $\pm 10^o$ for most values of γ and strong phase shifts.

B.1.6 x_s from $B_s \to D_s\pi$ (BTeVGeant study)

The PAC pointed out that the measurement of x_s was useful as a benchmark for assessing the experiment's ability to integrate its capabilities in proper-time resolution, tagging, and particle identification, as well as its overall sensitivity to B_s physics.

As described in Section 16.7, BTeV is capable of observing all x_s values less than 75 in one year of running. The improvement since the PTDR comes from two sources: there is an overall improvement which comes from using the full tagging power of BTeV; there is an additional improvement at large values of x_s which comes from the improved resolution on the proper decay time, which was achieved by reducing the amount of material in the pixel detectors.

B.2 Trigger/Detector Studies

We were asked to present a "clear and convincing case that all major detector systems are realizable and that the associated budgets are justified." The budget for the BTeV detector is justified in Part V of this proposal and supporting documents (the BTeV Work Breakdown Structure document). The first half of this request (all systems are realizable) is the subject of Part II and Appendix A of this proposal. We believe we have provided a convincing case.

The committee also raised specific questions about (1) the Vertex Trigger, (2) Pixel R&D, (3) EMCal, (4) Particle ID, (5) Muon Trigger, and (6) R&D Issues. These are addressed below. The committee requested that the following be included:

- Detailed and realistic simulations, including both physics and beam related backgrounds, secondary interactions and decays, all significant environmental effects such as multiple interactions, and detector/electronics noise.
- Clear and quantitative discussions of the trade-off between cost and performance for each detector subsystem, whenever substantial cost differences are involved.
- Studies should show how much the physics reach of the experiment is degraded if various components of the detector do not meet their design specification.

These have been included. The last two items are addressed in separate subsections below.

B.2.1 Vertex Trigger

The PAC commented that the vertex trigger is very ambitious, and that a convincing case based on careful studies was needed. They requested that we study the effects of non-perfect pattern recognition, beam misalignments and noise.

A more detailed discussion of this subject is given in Chapter 14. The results are summarized here.

The Level 1 vertex trigger has been extensively modified since the PTDR. This trigger is designed to work with the redesigned pixel system, which has less material than the PTDR system due to a reduction in the number of pixel planes per tracking station (two instead of three, see Chapter 4).

Our simulations are now significantly more realistic. They use GEANT (BTeVGeant) which includes effects from hadronic interactions, photon conversions, decays in flight, and delta rays. We introduce non-Gaussian tails to the hit distributions which are motivated by data from our 1999 beam tests. Our trigger simulation works at the "hit level" and therefore performs full pattern recognition. All studies are performed with an average of two interactions per beam crossing (the expected amount). One concern expressed by the PAC was that the doublet configuration would require too much time and swamp the trigger. The solution to this problem is to restrict the pattern recognition to a subset of pixel clusters to reduce the combinatorics.

We find that the trigger performance is at least as good as that described in the PTDR. We desire a rejection for minimum bias events of a factor of 100. Selecting Level 1 trigger "cuts" to give this level of rejection, we have looked at the trigger efficiency for several modes (see Table 14.1, Chapter 14) and find that they are generally much better than 50%. One mode ($B_s \to D_s^+ K^-$) has an expected efficiency of 74%.

We have found that this performance is exceptionally robust with respect to pixel inefficiencies and noise. Even adding 40 times the expected noise, we find only a slight decrease in trigger efficiency and a slight decrease in minimum bias rejection (see Figure 14.5 of Chapter 14). Pixel inefficiency does reduce trigger efficiency (Figure 14.5 again) but not dramatically.

We find minimal sensitivity to multiple interactions per event. If the two interactions are very close to each other, the trigger does get confused a small fraction of the time, but the effect on the trigger rate is insignificant (see Figure 14.6 of Chapter 14).

Finally, since we reconstruct full vertices and never rely on a beam constraint, beam misalignment is not a problem.

B.2.2 Pixel R&D

The PAC commended BTeV on "impressive progress" made on the pixel system in 1998-99. This progress has continued in 1999-2000. In a beam test, we have demonstrated that 50 μm $\times$ 400 μm pixels can provide the precise position measurements required by BTeV (details are provided in Appendix A). Moreover, we have verified that our pixel simulation program, also described in Appendix A, provides an accurate representation of the performance of real devices. Appendix A also describes our ongoing R&D on RF shielding and very recent results on the radiation hardness of FPIX readout circuits implemented in 0.25 μm CMOS.

The PAC encouraged BTeV to evaluate pixel detector designs using a smaller number of sensors to reduce the cost and complexity of the system. As stated above, our design now has two pixel planes per station, instead of three. Moreover, the design concept of a "shingled" support and cooling structure allows two planes of pixel detectors to be held on a single support. Together, these changes represent a significant reduction in the amount of material in the pixel detector, and a reduction in both the channel count and the system complexity.

The PAC noted that we were behind the timeline we presented in 1998, which called for us 1) to choose the sensor material and implant type by June, 1999, and 2) to have final sensor specifications by May, 2000. We have now made the decision that the pixel detector will use sensors fabricated from low-resistivity oxygenated n-type silicon, with n-implant pixels. We have not yet finalized our sensor specifications, but we expect to do so in the next year.

The PAC noted the progress that we made in 1998-99 towards establishing a reliable bump bonding capability, and we are continuing to make progress in this regard. The most notable recent development is the promising results we have obtained in tests of circuits bonded by MCNC using fluxless solder bumps.

The PAC stated that "a major decision remains as to which rad-hard" technology will be used for the pixel readout chip. In December, 1998, we made the decision to implement the third generation FPIX readout chip (FPIX2) in a commercial 0.25 μm CMOS process, using guard rings and enclosed-geometry transistors for radiation hardness. Our recent radiation damage test verifies that this was a good decision. We expect to complete the FPIX2 design in Fall, 2000, and have devices in hand by early 2001. We expect this device will be radiation hard and will meet all of our pixel readout requirements.

The PAC stated that it would like to understand better the extent to which the FPIX1 readout chip met BTeV's requirements, and what types of improvements were planned. A fully functional, radiation hard, FPIX1 would have met *all* of BTeV's requirements. However, in addition to being radiation hard, FPIX2 will be superior to FPIX1 in the following ways:

- A 3-bit FADC, instead of 2-bit, will provide better sensor performance monitoring ability, as well as excellent charge-sharing information.
- Smaller discriminator threshold dispersion will allow a lower threshold to be used, probably under 2000 e^-. This will be especially important for the readout of radiation damaged sensors, which may yield a smaller signal than undamaged sensors.
- Better leakage current compensation will allow FPIX2 to be used to read out heavily damaged sensors without having to adjust the amplifier feedback current.
- Simplified end-of-column logic will increase the readout bandwidth of FPIX2 by approximately a factor of two over FPIX1.
- An increase in token passing speed made possible by the use of smaller feature size transistors will allow even higher readout bandwidth, or columns containing more than 160 rows of pixels, or both.
- A significantly reduced I/O pin count will allow a less complex high density interconnect to be used.

As is described briefly in Chapter 4, progress is also being made on the development of a low-mass integrated cooling and mechanical support structure. We have received, and are thermally testing, a first "fuzzy carbon" prototype. By the end of this summer, we expect to receive two new prototypes that can be used in tests of sensor modules.

In general, our R&D focus is shifting from the level of individual components and technologies to the system level. The PAC encouraged us to "push towards a system prototype that would test not only the electrical performance, but also the mechanical and thermal properties." We agree that this is a high priority and we intend to mount such a test as soon as possible. In addition, our R&D plan, and the cost estimate for this proposal, both anticipate a "3%" system test, followed by a "10%" system test. Assuming that these tests can be done in C0, we expect to include as part of the tests an RF shielding solution that we will have verified using the beam simulator described in Appendix A. We believe that these tests will allow us to set achievable goals for the pixel detector, and to formulate a detailed and reliable construction plan.

B.2.3 EMCal

The PAC requested comprehensive studies of γ and π^0 reconstruction using a full (GEANT) simulation of the electromagnetic calorimeter. They also noted that the difficulty in obtaining the required quantities of $PbWO_4$ is a serious concern.

We have implemented a full GEANT simulation of the electromagnetic calorimeter, and used it to study the efficiency and backgrounds for final states with π^0s. The results are presented in Chapter 16 and were summarized above (Sections B.1.1 and B.1.3). BTeV's ability to study states with γ's and π^0's using its $PbWO_4$ electromagnetic calorimeter has been vindicated. Using full GEANT simulations with a complicated underlying event and accompanying minimum bias events, we can successfully reconstruct even the very low energy photons from these decays and can suppress the combinatoric background. We expect to reconstruct a factor of 7 more $B \to \rho\pi$ decays than LHC-b with 5 times better signal-to-background (see Part IV).

As for the difficulty in obtaining the required quantities of $PbWO_4$, we have begun discussions with both Russian (the Bogoroditsk Techno Chemical Plant) and Chinese suppliers in Beijing and Shanghai. CMS production is scheduled to finish in 2005. We have visited the crystal production facilities in Russia and in China. Our Russian and Chinese collaborators have been most helpful in setting up these visits. The Russians have already been producing production crystals (>6000) and are eager to have our business. They have supplied prices and possible schedules. The Chinese have not started production as of this writing, but they are very close to doing so. They are also very interested in BTeV production. Our collaborators at Shandong University are also interested and capable of producing $PbWO_4$ crystals. We would like to initiate a startup program with them as soon as possible. Generally we think it important to have more than one supplier of crystals. Because of the open nature of the BTeV detector, crystal installation can proceed in place over a long period of time.

B.2.4 RICH

The PAC commented that high quality particle identification, primarily K/π separation, is essential for BTeV's physics objectives, both for signals and tagging. They felt that the effort on this detector should be substantially strengthened over the next year.

The effort on the RICH has been strengthened over the past year. For more information see Chapter 6 and Appendix A. A more detailed simulation of this detector has also been implemented and used in the physics simulations performed for this proposal (see Chapter 16 and Section B.1.2 above).

B.2.5 Muon Trigger

The PAC expressed concern that only three (high segmentation) detector stations were planned for the muon system in each arm. Their primary concern was the resistance of the muon trigger to spurious tracks and backgrounds, effects which were not included in the studies performed for the PTDR.

We have added a view to each detector station, so that there are now 4 views instead of 3. This adds redundancy and should help with the rejection of spurious hits and tracks. We have also performed a full BTeVGeant simulation for minimum bias events and $B \to J/\psi K_s$. Hadronic interactions, conversions, etc., are all included in the simulation. These simulations predict that the innermost proportional tubes in our system will have occupancies of ~20%, although the occupancy falls off rapidly ($\sim 1/r^2$) with distance from the beam.

Our simulations show that a realizable Level 1 trigger with a rejection factor for minimum bias events of 500–600 is possible with high efficiency for modes of interest (50% for $B \to J/\psi K_s$). These simulations were generated with only 3 views per stations instead of 4. The fourth view can only improve the results. More detailed information on this trigger simulation is given in Section 8.3.

B.2.6 R&D Issues

After the April 2000 PAC meeting, the committee requested that we discuss major remaining R&D issues. All of the detector subsystems have detailed plans for future R&D; these are discussed in Appendix A.

B.2.7 Cost/Performance Trade-offs

The PAC requested that we discuss the trade-off between cost and performance "whenever substantial cost differences are involved."

In the RICH detector, the cost of photo-detectors is a significant fraction of the total cost. We have performed a study of efficiency for a specific state ($B \to \pi\pi$) versus photo-detector coverage (*i.e.* the number of photo-detectors we have to buy). The results are presented in Figure 6.6 of Chapter 6.

In the EMCal, we have also made a compromise between coverage and cost. As discussed in Chapter 7, the calorimeter cost can be parameterized roughly as

$$T\ (\$) = 700(\$) \times N_c + 3,400,000(\$), \tag{B.1}$$

where N_c is the number of crystals and T the total cost. The fixed costs represent mainly startup of crystal production, the crystal container, the light calibration pulsar and electronics development. Figure 7.1 of that chapter shows the efficiency as a function of calorimeter radius for the reaction $\overline{B}^o \to D^{*+}\rho^-$. Weighing this efficiency versus total cost, we adopted an outer radius of 160 cm, corresponding to 23,700 crystals for both arms.

The pixel detector is the heart of the experiment. The number of pixel planes is defined by beam size. Preliminary studies indicate that there is minimal gain in performance from increasing the size of the pixel planes. These studies indicate that decreasing the size of the planes may be possible, but this is a complicated analysis. Because of the importance of this detector, we are taking a conservative approach and we have not decreased plane size. We intend to perform a detailed analysis, taking into account the important issues. If at that time there is strong evidence indicating minimal impact, we will reduce the plane size.

B.2.8 Degradation of Performance and Physics Reach

The PAC commented: "Simulations should ... be used to analyze how much the physics reach of the experiment is degraded if various components of the detector do not meet design specification."

Section 16.9 of this proposal is devoted to a discussion of how degraded performance of detector subsystems would affect our physics reach. The section is reasonably short and we will not attempt to summarize it here.

B.3 Comparisons to Other Experiments

The PAC concluded:

- BTeV has a substantial physics reach beyond that of e^+e^- experiments at the $\Upsilon(4S)$.
- BTeV will likely have a physics reach substantially beyond that of CDF and D0, including their beyond-the-baseline upgrades.
- BTeV may be superior to LHC-b in three main areas: vertexing, triggering, and photon energy resolution.

Their main request was: "The Committee would like to see a clear and convincing demonstration that BTeV has a physics reach superior to LHC-b."

This issue is addressed in Part IV of this proposal. Comparing to our detailed simulations, we show that BTeV is better than LHC-b in 'high-priority' final states with all charged particles. For final states with γ's, π^0's, η's or η''s, BTeV is far superior. Furthermore, BTeV will write to tape 5 times more b events than LHC-b, allowing for a wider range of physics studies. This is important because we cannot anticipate all the physics that will be interesting at the time BTeV actually runs, and new ideas and phenomena may appear or become relevant.

B.4 Staging and Commissioning Scenarios

The PAC has requested a staging and commissioning scenario for BTeV compatible with minimal luminosity reduction to CDF and D0.

A more detailed discussion of our plans for deployment is given in Chapter 11 of the proposal. We request the following:

- We would like to be installed with at least one arm operational and receive enough luminosity to make at least one measurement (such as $\sin(2\beta)$, B_s mixing, and/or studies of $K^*\gamma$) before LHC turns on.

- We would prefer to finish our installation and checkout of the first arm prior to installation of the second. Our physics program can begin as soon as the first arm is completed.

We assume that the various detector subsystems in the first arm can be installed individually as they become ready. As discussed in Chapter 11, this is possible because the detector is not monolithic but is made up of individually mounted and independent subsystems. Short term accelerator shutdowns could be used for this purpose.

As subsystems are installed, we will initially want short runs (at the end of stores, etc.) for checkout and commissioning studies. It would be acceptable to us if these runs were kept brief so that the net impact on delivered luminosity to CDF and D0 was minimal (a 1% diminishment or so). A principle goal during this period will be to debug and commission the level 1 and 2 triggers and data acquisition system, which can't be tested in external beam tests. Some of this can be done with a wire that can be moved into the beam halo without disturbing the luminosity in the other two collision regions.

Once the full arm is installed we request a period during which we receive longer, high luminosity runs. This period will allow us to accomplish a limited physics program prior to LHC turn-on (as discussed above), and we anticipate this period will take roughly four months. BTeV believes that this running will have a huge impact on our ability to commission the detector and believes that the impact on CDF and D0 can be kept low so that their physics reach is not noticeably affected. A reasonable goal might be to make sure that the net effect on CDF and D0 during this period was no more than 10%.

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